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Relationship Between Plasma Energy and Gas Generation in an Electrothermal-Chemical Gun

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1. INTRODUCTION

The electrothermal-chemical (ETC) gun utilizes electrical energy to create a low-mass, high-energy plasma which initiates and (hopefully) controls the vaporization and combustion of the propellant in the combustion chamber. Although the total effect of electrical energy input on the rate of propellant vaporization in the ETC gun is unknown, it is assumed that the gas generation can be controlled by tailoring the delivery of electrical energy to the combustion chamber. Control of the gas generation is required in order to obtain the desired chamber pressure profile to achieve optimal gun performance.

Figure 1 shows the five major components in an ETC gun: (1) the power supply (prime power and intermediate storage batteries); (2) the pulse forming network; (3) the plasma cartridge (capillary); (4) the combustion chamber; and (5) the barrel and projectile. The plasma cartridge (Figure 1) is a tube, usually polyethylene, containing a fuse wire. When high voltage is supplied to the plasma cartridge, the resulting current vaporizes the fuse inside the capillary. Since temperatures of many thousands of degrees are reached in the capillary, the radiation heat flux from the plasma ablates additional material from the capillary wall. The plasma flows into the combustion chamber and ignites the propellant, which generates gas and accelerates the projectile down bore.

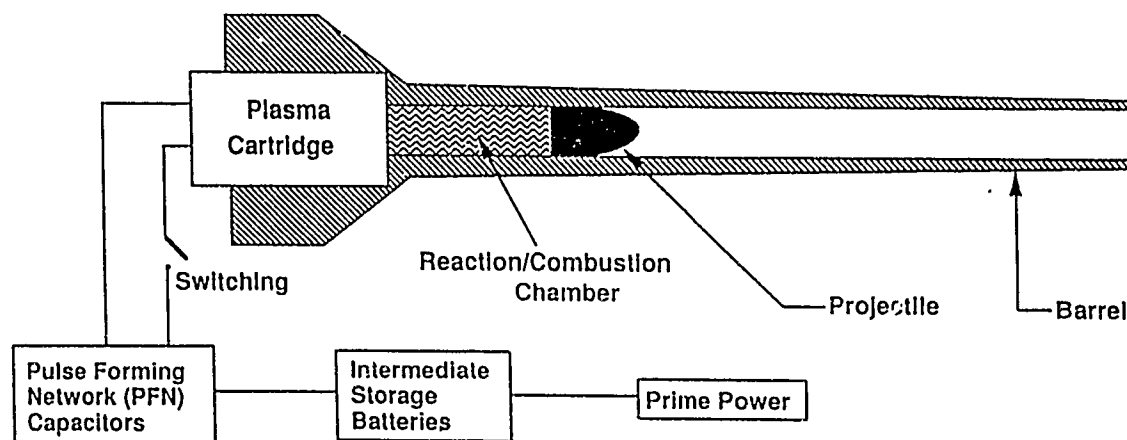


Figure 1. An electrothermal-chemical (ETC) gun.

To demonstrate repeatability, control, and predictability of the ETC concept in small-caliber guns, the FMC Corporation under the Electrical Enhancement Factor (EEF) follow-on contract performed a series of firings using 30-mm, subscale experiments for both tank and artillery systems. Many propellants and designs were investigated. However, the propellant considered in this report is a mixture of hydroxylammonium nitrate (HAN) and other components. Additional components were added to increase the viscosity and to maintain uniform performance characteristics throughout the propellant bed. Electrical energy input, loading density, and the specific geometry of the capillary and the propellant chamber were also varied.

A study to determine the relation between the plasma energy input and the gas generation during the plasma injection phase is undertaken using FMC experimental data. The purpose of this study is to obtain the gas generation information for an interior ballistic model of the ETC process and to investigate the control of the pressure-time profile through the delivery of electrical energy.

The relationship between plasma energy (electrical energy) and gas generation (decomposition) of a propellant in an ETC gun is investigated by using an inverse analysis model (Wren and Oberle 1992). The model computes the gas generation of the propellant by incorporating experimental measurements of pressure, projectile travel, and electrical energy, along with the initial charge mass and projectile mass, a table of calculated thermochemical properties (impetus, ratio of specific heat, covolume, and temperature) relative to electrical energy density, and the effect of air in the combustion chamber (since ETC firings can have large initial ullage).

The inverse analysis model uses experimental data of pressure, electrical energy, and projectile travel to calculate a propellant mass consumed at each independent timestep based on energy conservation, whereas a conventional interior ballistic model (such as IBHVG2) uses known burning rates, gun parameters, and propellant characteristics to provide the maximum pressure and muzzle velocity.

2. EXPERIMENTAL FIXTURE

A description of the experimental gun parameters is shown in Table 1.

Table 1. Gun Parameters

Gun Fixture:	30 mm, artillery
Travel:	51 calibers
Projectile Mass:	339 g
Chamber Volume:	166 cm ³
Electrical Energy Input:	30-150 kJ
Propellant:	Two types, both including HAN

The propellant is distributed in the chamber in up to four unit modules, and an ullage tube is used at the center of the propellant chamber to distribute plasma uniformly through the charge. Figure 2 shows a schematic of the combustion chamber for the ETC gun described in Table 1.

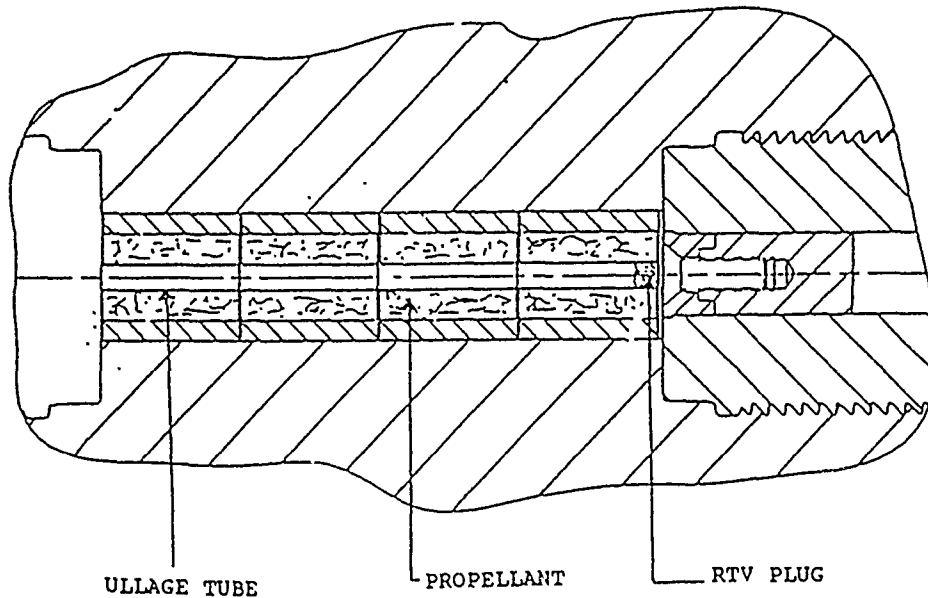


Figure 2. Schematic of combustion chamber.

3. NUMERICAL ANALYSIS

To investigate the relation between the electrical energy input and the consumed mass of the propellant, an inverse analysis is applied. The inverse analysis computes the decomposition of propellant based on the energy balance equation at the given time:

$$Q = U + W + \text{LOSSES} , \quad (1)$$

where Q is the total energy available (chemical and electrical), U is the internal energy of the gas, and W is the work performed by the gas. Experimentally measured pressure, plasma energy, projectile travel, and the calculated thermochemical properties (Freedman 1982) of the propellant serve as the input parameters used to calculate the energy balance between projectile kinetic energy, gas kinetic energy, internal energy, and heat loss. Lagrange assumptions are used to calculate the pressure gradient. The calculated thermochemistry is assumed to be variable with the electrical energy density, which is the ratio of input plasma energy to consumed propellant mass. The governing equations have been described elsewhere (Wren and Oberle 1992), and only modifications will be discussed in this report.

Initially, the inverse analysis of the experimental data without the heat loss function showed a discrepancy (about 10–15%) in the mass of the propellant consumed at muzzle exit compared to experiment. Since some energy is lost to the barrel and the plasma channel during the combustion process, a calculation for heat loss was added to the inverse code. The energy lost due to heat transfer to the walls is given by a standard heat loss equation (Robbins and Raab 1988):

$$E_h = \int_0^t A_w h (T - T_w) dt, \quad (2)$$

where A_w is the area of the wall exposed to the propellant gas, h is the heat transfer coefficient, T is mean gas temperature, and T_w is the wall temperature. The (heat transfer coefficient) h is given by

$$h = \lambda \bar{c}_p \bar{\rho} \bar{v} + h_0, \quad (3)$$

where λ , \bar{c}_p , $\bar{\rho}$, and \bar{v} are the Nordheim heat transfer coefficient, specific heat at constant pressure of propellant gas, mean gas density, and mean gas velocity, respectively, and h_0 is the free convective heat transfer coefficient. The parameter λ is given by

$$\lambda = \left[13.2 + 4 \log_{10} (100D) \right]^{-2}, \quad (4)$$

where D is diameter of the bore and the wall temperature is

$$T_w = \frac{E_h + fE_{br}}{c_{pw} \rho_w A_w D_w} + T_0, \quad (5)$$

where C_{pw} , ρ_w , D_w are heat capacity, density of the wall material, and the heat-penetrated thickness of the wall (Robbins 1988), respectively. E_{br} is the energy loss for work against bore resistance, f is friction coefficient, and T_0 is the initial temperature of the wall. For this inverse analysis, E_{br} is assumed to be zero since the tube is smooth bore, and the parameters for the properties of steel (Robbins 1992) are used for the wall material. All input parameters are held fixed in the calculations which follow.

Projectile motion is calculated from radar data. A program was developed to determine the times corresponding to the maximum amplitudes of sine waves. The wavelength of the radar signal inside the gun tube is calculated by

$$\frac{1}{\lambda_g^2} = \frac{1}{\lambda_0^2} - \frac{1}{\lambda_c^2}, \quad (6)$$

where λ_g is the wavelength in the gun tube, λ_0 is free-space wavelength, and λ_c is cut-off wavelength. (Vest et al. 1955).

Restating equation (6), we have

$$\lambda_g = \left[\left(\frac{1}{\lambda_0} \right)^2 - \left(\frac{1}{\lambda_c} \right)^2 \right]^{-\frac{1}{2}}. \quad (7)$$

The cut-off frequency f_c is

$$f_c = \frac{1.84 C}{\pi D}, \quad (8)$$

where C is the speed of light and D is the diameter of the gun tube (Evans 1985; Ware and Reed 1958). Because the wavelength is equal to the speed of light divided by the frequency, substituting equation (8) into equation (7) gives

$$\lambda_g = \left[\left(\frac{f_0}{C} \right)^2 - \left(\frac{1.84}{\pi D} \right)^2 \right]^{-\frac{1}{2}}. \quad (9)$$

With the interferometer frequency of 10.525 GHz, the wavelength inside the barrel is 3.4272 cm.

The projectile position at time t will be:

$$x(t) = \sum_{i=1}^t \frac{\lambda_g}{2 (T_i - T_{i-1})} \delta t + x_0, \quad (10)$$

where $(T_i - T_{i-1})$ is the travel time for each half wavelength and x_0 is the position of the projectile at starting point.

The calculated times for projectile exit are in agreement with the results obtained from the radar signals and the measured pressure profiles at the muzzle exit. These data are also verified by calculating the velocity of the projectile using a second-order polynomial spline fit method. The percent differences of these velocity computations range from 1–4% compared to the results obtained from the Weibel program (commercial software to calculate velocity from the radar trace). Since the experimental design includes a ullage tube attached to the plasma capillary, there is an initial time delay before the ullage tube ruptures and pressure is generated in the combustion chamber. Observation of the current and voltage histories of the plasma compared to the pressure-time history in the combustion chamber show a time delay of approximately 0.5 ms. Thus, the calculation begins when the pressure gage begins to record.

4. RESULTS AND DISCUSSIONS

The results of the mass consumed versus plasma energy input are divided into 13 groups according to the configurations of the firings as listed in Table 2. The group identification includes the group

number and shot numbers for that group. The ullage dimensions are the inner diameter and wall thickness of the ullage tube, respectively (see Section 2). The capillary dimensions are the inner diameter and length of the polyethylene liner in the plasma capillary.

Table 2. Shot Configuration

Group No. (Shot No.)	Charge Loaded	Ullage Structure	Ullage Dim. ID/t ^a	Cap. Dim. ID/L ^b
1 (Shots 07-08)	Full charge, 1 module	with RTV plug	0.974/0.022	0.25/5.16
2 (Shots 09-11)	Full charge, 1 module	with RTV plug	0.528/0.042	0.25/5.16
3 (Shots 12-13)	Full charge, 1 module	with RTV plug	0.374/0.032	0.188/5.16
4 (Shots 15-16)	Full charge, 1 module	with RTV plug	0.401/0.032	0.188/5.16
5 (Shots 17-18)	Full charge, 1 module	with RTV plug	0.323/0.042	0.188/5.16
6 (Shots 23-25)	Full charge, 4 module	without RTV plug	0.401/0.022	0.25/5.16
7 (Shots 27-28)	Full charge, 4 module	without RTV plug	0.354/0.042	0.25/5.16
8 (Shots 30-32)	Full charge, 4 module	without RTV plug	0.374/0.032	0.25/5.16
9 (Shots 36-37, 46-48)	Full charge, 4 module	with RTV plug	0.374/0.032	0.25/5.16
10 (Shots 38,40)	3/4 charge, empty in rear	with RTV plug	0.374/0.032	0.25/5.16
11 (Shots 39,41)	3/4 charge, empty in front	with RTV plug	0.374/0.032	0.25/5.16
12 (Shots 43-44)	1/2 charge, empty in front	with RTV plug	0.374/0.032	0.25/5.16
13 (Shots 195-208)	Full charge	—	0.455/0.06	0.313/5.16

^a ID = inner diameter and t = thickness; ^b L = length

Figures 3–15 show the calculated propellant mass consumed versus experimental plasma energy for each group, and Figure 16 shows the plasma energy and the propellant consumed as a function of time for group 13.

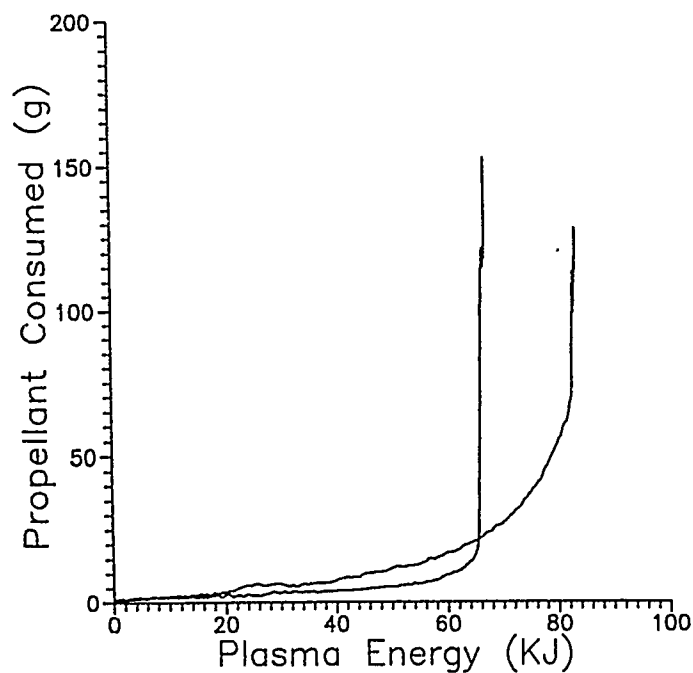


Figure 3. Group 1 (shots 7 and 8) - Propellant consumed vs. plasma energy.

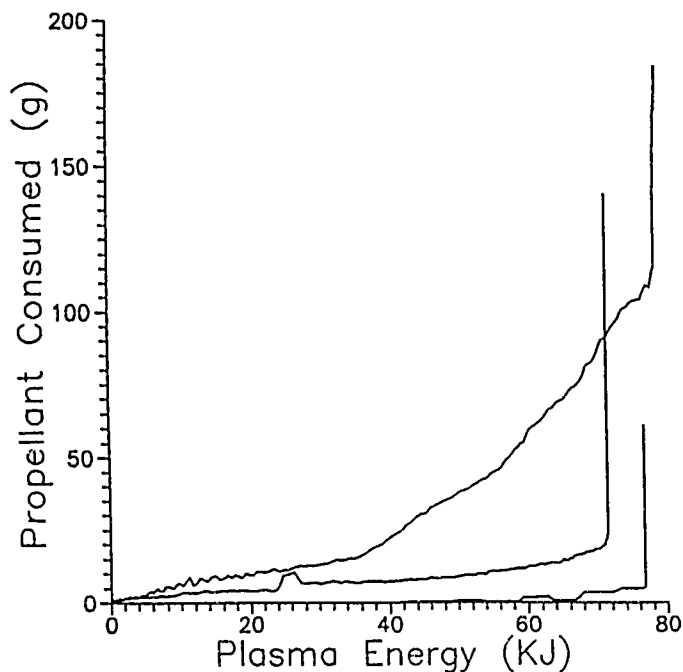


Figure 4. Group 2 (shots 9–11) - Propellant consumed vs. plasma energy.

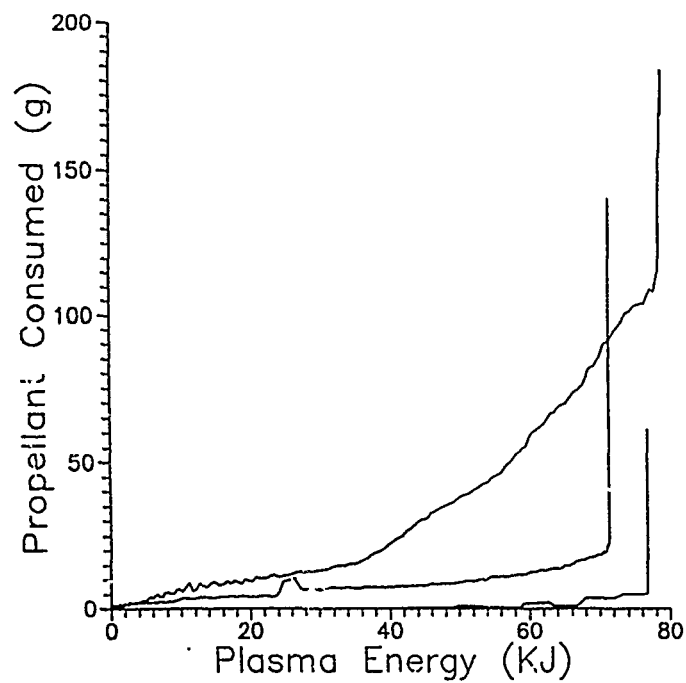


Figure 5. Group 3 (shots 12 and 13) - Propellant consumed vs. plasma energy.

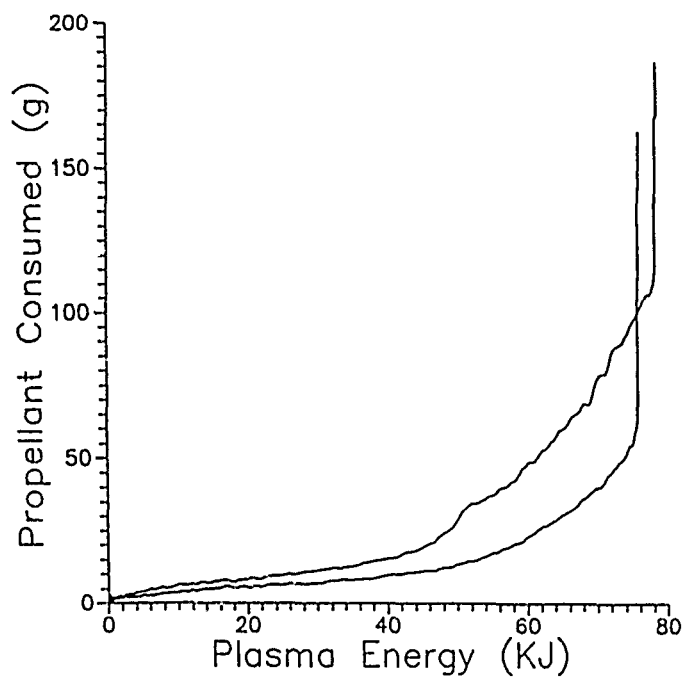


Figure 6. Group 4 (shots 15 and 16) - Propellant consumed vs. plasma energy.

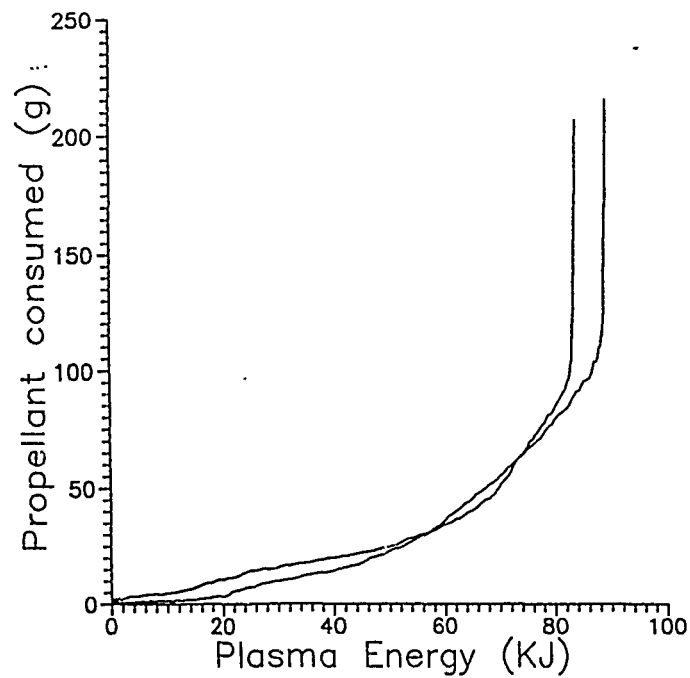


Figure 7. Group 5 (shots 17 and 18) - Propellant consumed vs. plasma energy.

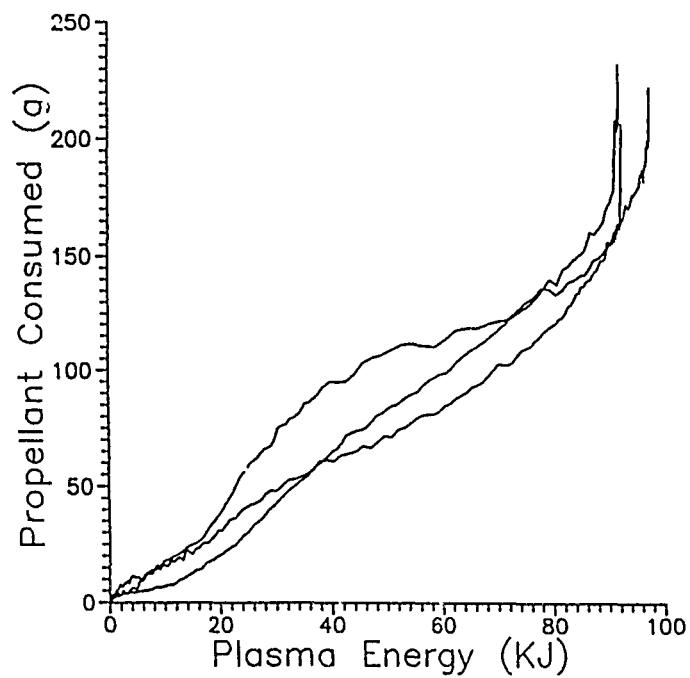


Figure 8. Group 6 (shots 23-25) - Propellant consumed vs. plasma energy.

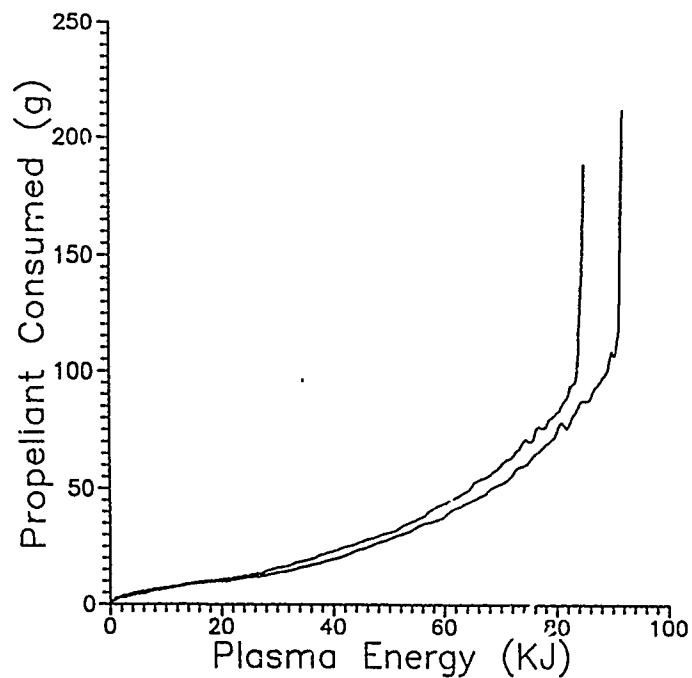


Figure 9. Group 7 (shots 27 and 28) - Propellant consumed vs. plasma energy.

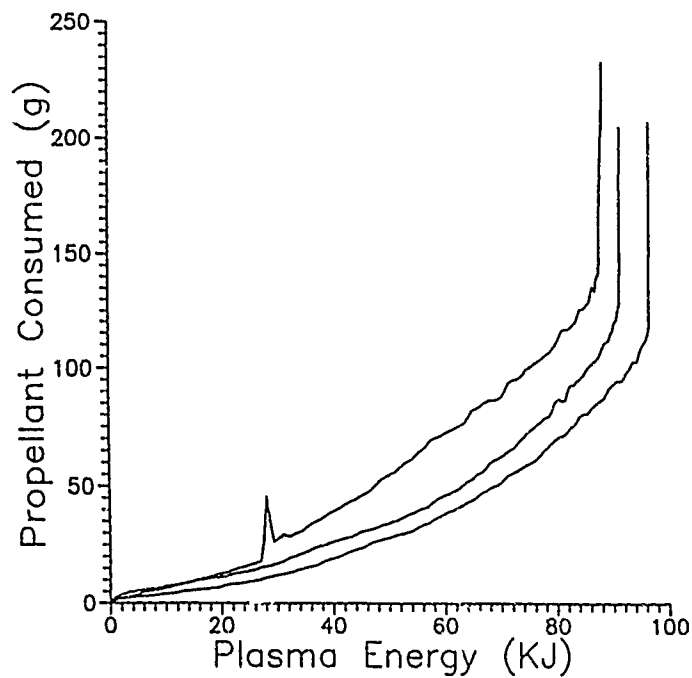


Figure 10. Group 8 (shots 30-32) - Propellant consumed vs. plasma energy.

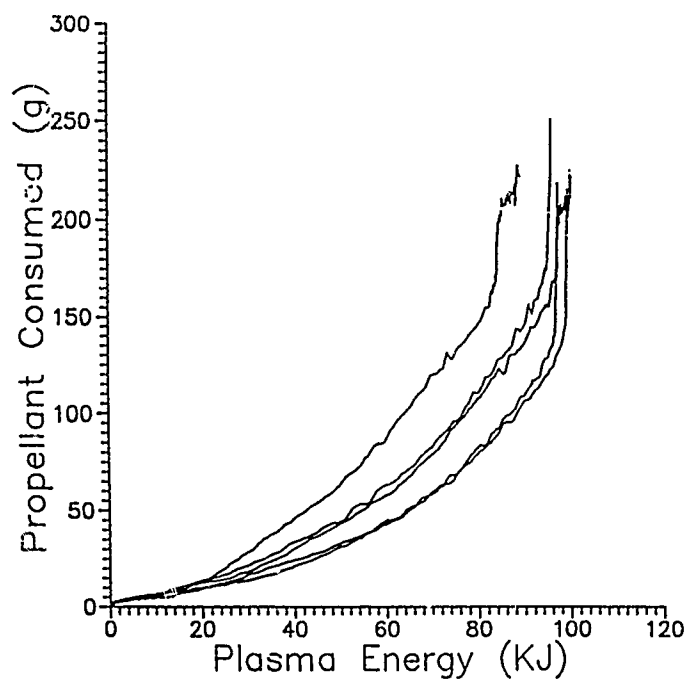


Figure 11. Group 9 (shots 36, 37, and 46-48) - Propellant consumed vs. plasma energy.

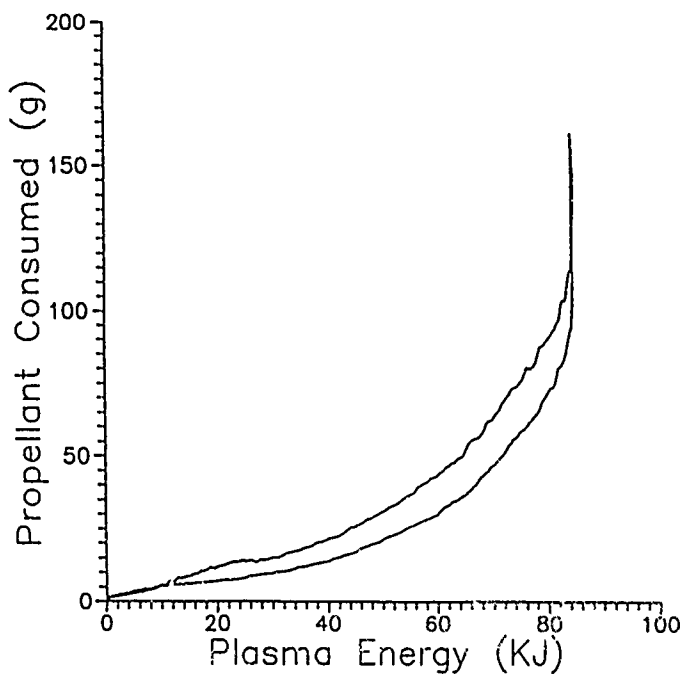


Figure 12. Group 10 (shots 38 and 40) - Propellant consumed vs. plasma energy.

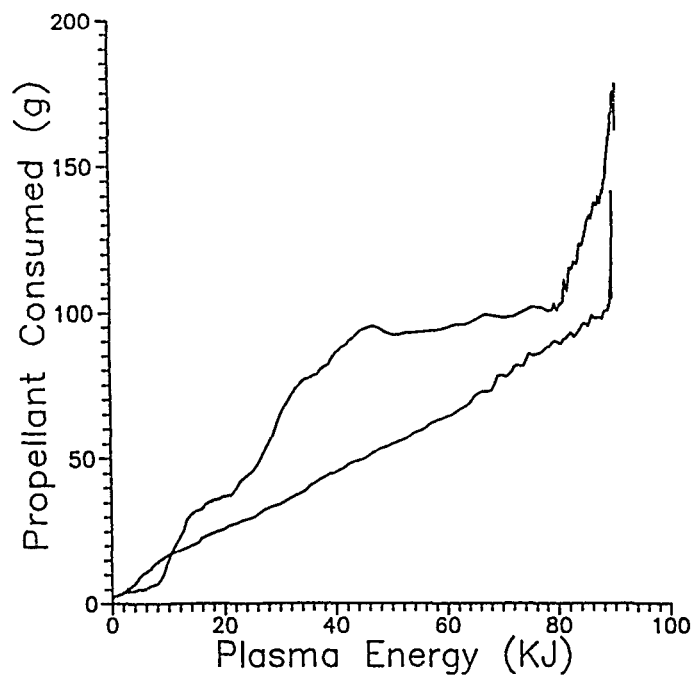


Figure 13. Group 11 (shots 39 and 41) - Propellant consumed vs. plasma energy.

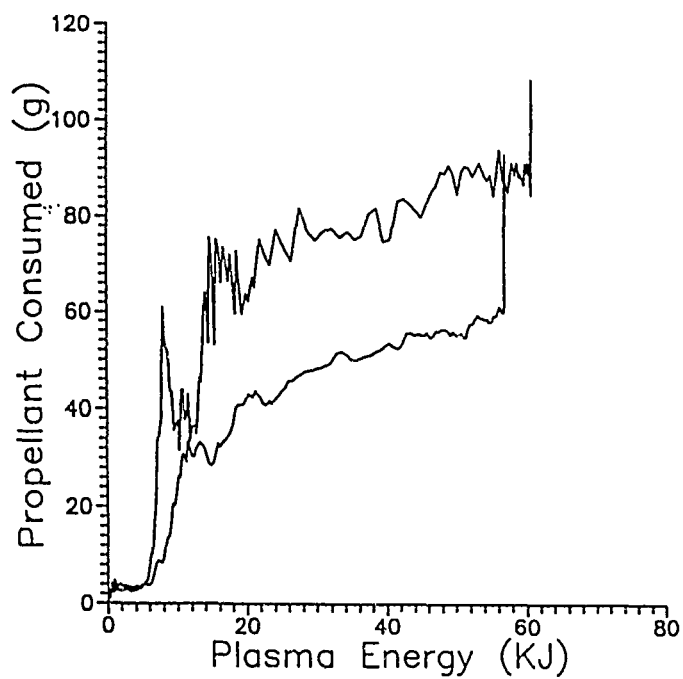


Figure 14. Group 12 (shots 43-44) - Propellant consumed vs. plasma energy.

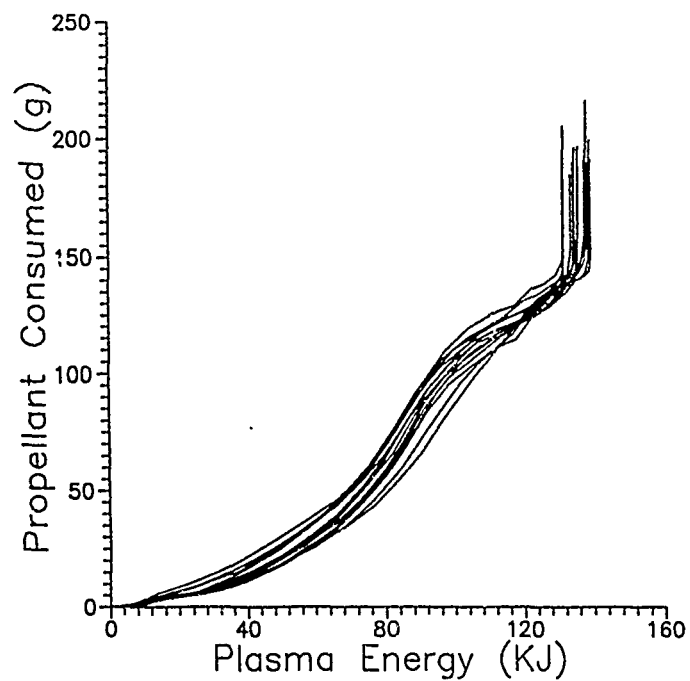


Figure 15. Group 13 (shots 195-208) - Propellant consumed vs. plasma energy.

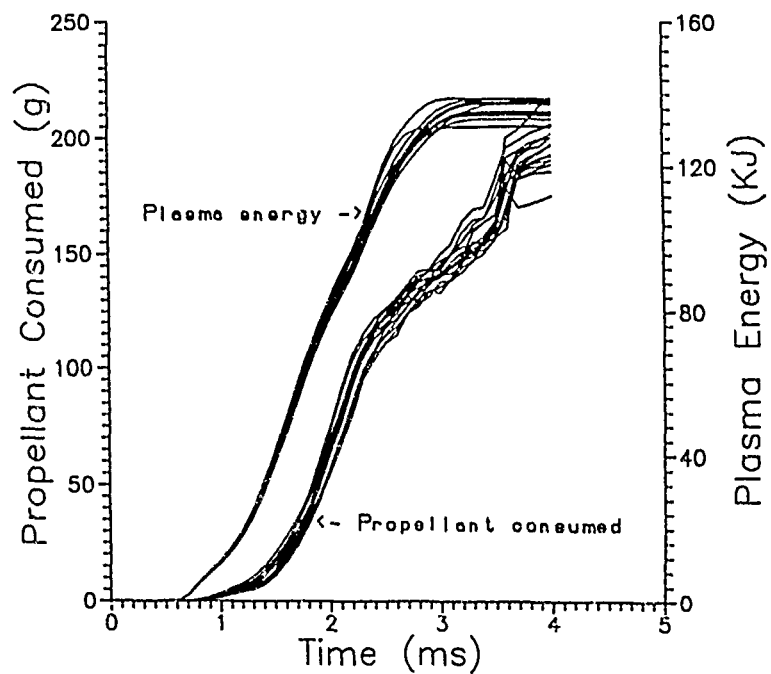


Figure 16 Group 13 (shots 195-208) - Plasma energy and propellant consumed vs. time.

The configuration for this series of firings was changed frequently, especially the centercore ullage of the combustion chamber (see Table 2). The following observations are made from the series of firings studied:

- The cases of partial propellant loads with ullage in the front of propellant chamber give a non-repeatable pressure profile and, as a result, the propellant consumed calculated from the inverse code is variable within a group (see Figures 13 and 14).

- In general, the decomposition rate of propellant in the combustion chamber seems to be a strong function of the centercore ullage configuration in both dimension and material. For the first 40 firings analyzed, no consistent relation between the gas generation and the electrical energy can be drawn. Even within the same group, the inferred mass consumed of the propellant in the combustion chamber was not repeatable with respect to the plasma energy. This suggests that the plasma energy only plays an important role in the ignition of the propellant. In the majority of the cases studied, the amount of propellant consumed at the time that the electrical energy reaches its maximum is approximately 50–60%.

However, utilizing a different design ullage tube and a different HAN-based propellant, firings 195–208 displayed more repeatable results (see Figures 15 and 16). The rate of propellant consumed is more linear in nature. Approximately 65% of the propellant is consumed at the time plasma energy is terminated. The rate of propellant consumption significantly decreases after the termination of plasma energy, suggesting that the plasma is a factor in the combustion process.

For this particular ullage design and propellant (firings 195–208), the average amount of propellant consumed and the plasma energy input during the early stage of the combustion process (to ~2.5 ms) are related by

$$y = 1.76734 - 0.164044x + 0.0116825x^2, \quad (11)$$

where y is mass of propellant consumed in grams and x is the plasma energy input in kJ. Plasma energy after this time is not considered to be a controlling factor in the amount of propellant consumed.

5. CONCLUSIONS

The relationship between the decomposition of the propellant and plasma energy was studied for a 30-mm ETC gun using two HAN-based propellants. The results from this study suggest that the propellant gas generation rate depends strongly on the design of the cartridge and the properties of the propellant rather than on the plasma energy input. However, the repeatability series (shots 195–208), show a potential for a relationship between the gas generation rate and plasma energy input for the particular gun configuration and propellant.

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